

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE  
APPLICATION FOR LETTERS PATENT

William S. Frommer  
Registration No. 25,506  
FROMMER LAWRENCE & HAUG LLP  
745 Fifth Avenue  
New York, New York 10151  
Tel. (212) 588-0800

## Description

- 1 The invention relates to a modulation/demodulation method for multi-amplitude digital modulated signals with non-equidistant phases transmitted via an orthogonal frequency division multiplexing (OFDM) communication channel and also refers to an OFDM system for the transmission of  
5 information by multi-amplitude digital modulated signals from a transmitter to a receiver via a radio channel.

Orthogonal frequency division multiplexing (OFDM) has gained increasing interest in wireless communication systems during the last years, in particular  
10 for DAB (Digital Audio Broadcast) and DVB-T (Digital Video Broadcast Television). It has been considered for transmitting high data rate over frequency selective radio channels.

The principle of OFDM transmission technique is to devise an available  
15 bandwidth into several subchannels with smaller bandwidths. Thus the symbol length increases and the inter symbol interference (ISI) is combated. On the other hand, each subchannel is considered to be frequency non-selective. The amplitude and phase distortion caused by multipath effects is accordingly described by one factor.

20 In coherent transmission systems that distortion is removed by channel estimation. For this purpose known symbols are sent on pilot subcarrier(s). On the receiver side the amount of channel distortion is processed from the received known symbols and is used to correct the rest of the data before  
25 demodulation.

Channel estimation is not required, if differential modulation is used. The information is encoded in the ratio of successive symbols on the same subcarrier. Thus, the channel distortion is cancelled at the receiver, since it is  
30 assumed to be constant during successive OFDM symbols.

However, differential modulation and demodulation have been only described for low-order single-amplitude modulation schemes, such as PSK (Phase-Shift Keying) and QPSK (Quadrature Phase-Shift Keying). As for a specific example, reference is made to document DE 195 40 250 C1 describing a demodulation

1 scheme based on the assumption that the demodulated complex symbols are  
associated to respectively transmitted symbols via a rotational symmetric  
constellation diagram so that approximative estimations for the phase-shift  
lead to applications with reasonable results.

5

For multi-amplitude signals such as QAM (Quadrature Amplitude Modulation)  
only coherent modulation is used, and thus channel estimation is always  
required (see e.g. EP 0 734 132 A2).

10 It is an object of the present invention to teach a more simple modulation/  
demodulation method and system for multi-amplitude digital modulated  
signals with non-equidistant phases, in particular QAM signals transmitted via  
an OFDM communication channel without the necessity of using pilot carriers.

15 According to the teaching and the characterizing features of claim 1, this  
problem is solved with the idea that the amplitudes of said digital modulated  
signals should be separately and coherently processed, whereas for the phases  
of respectively subsequent symbols on the same subcarrier differential  
modulation and demodulation is provided.

20

Advantageous details, improvements and embodiments are the subject of  
dependent claims.

25 An orthogonal frequency division multiplexing (OFDM) system for the trans-  
mission of information by multi-amplitude digital modulated signals from a  
transmitter to a receiver via a radio channel in accordance with the invention  
is the subject-matter of and defined in claim 9. Specific embodiments and  
advantageous supplements and improvements are defined in further dependent  
claims.

30

For a comprehensive explanation of the invention the following description is  
divided in chapters.

35 In **Chapter I** the OFDM transmission model used for simulations and the  
channel models are first described.

1 In **Chapter II** the simulation of coherent modulated 16 QAM is presented.

In **Chapter III** the principle of the combined coherent/differential (henceforward called quasi-differential) modulation for 16 QAM signals is  
5 described as well as the way it was implemented according to a best mode presently known.

In **Chapter IV** the simulation results of both techniques are compared in terms of BER (Bit Error Rate) performance in an AWGN (Additive White Gaussian  
10 Noise) channel and in a multipath channel.

Finally as a **Summary** a brief comparison of both systems with respect to implementation complexity will conclude the present description of the  
15 invention.

In the following description reference will be made to the accompanying drawings in which

**Fig. 1**

20 is a block diagram of an OFDM system with features according to the invention;

**Fig. 2**

25 is a diagram of the BER performance of coherent 16 QAM signals in an AWGN channel and multipath channel, respectively;

**Fig. 3**

is a constellation diagram of 16 QAM symbols before and after phase-differential encoding;

30 **Fig. 4**

depicts a block diagram implementation of a quasi-differential phase encoder (transmitter side);

**Fig. 5**

is a block diagram of the implementation of a quasi-differential phase decoder (receiver side);

35

**Fig. 6**

shows a data frame structure as used for simulations;

- 1 **Fig. 7** is a diagram of the BER performance of quasi-differential 16 QAM signals in AWGN and multipath channels, respectively;
- 5 **Fig. 8** visualizes a diagram of a BER performance comparison of coherent and quasi-differential 16 QAM in an AWGN channel;
- 10 **Fig. 9** is the diagram of a BER performance comparison of coherent and quasi-differential 16 QAM signals in multipath channels; and
- 15 **Fig. 10** shows constellation diagrams of received QPSK and 16 QAM signals at different stages with an assumed SNR (Signal-to-Noise Ratio) of 35 dB wherein
- **Fig. 10A** visualizes received QPSK signals in a multipath channel;
  - **Fig. 10B** is a plot of received 16 QAM signals in a multipath channel;
  - 20 - **Fig. 10C** shows the stage of received QPSK signals after differential phase decoding;
  - **Fig. 10D** is a Q/I plot of received 16 QAM signals after differential phase decoding;
  - 25 - **Fig. 10E** depicts a plot of received QPSK signals after passing a hardlimiter on the receiver side; and
  - 30 - **Fig. 10F** represents a Q/I plot of received 16 QAM signals after amplitude correction.

## Chapter I: System Simulations

- 35 In order to evaluate both the coherent transmission scheme and the quasi-differential transmission scheme according to the invention in different environments a baseband simulation tool known under the tradename COSSAP

1 has been used.

The OFDM transmission model used for such simulations is shown in Fig. 1. Briefly, this OFDM system works as follows: The uncoded data stream is first  
 5 modulated in 16 QAM symbols. Then  $(N-N_{sel})$  virtual carriers ( $N$  = maximum carriers for FFT;  $N_{sel}$  = selected carriers) are inserted in the band edges of each OFDM symbol, since they are not used to transmit data. After IFFT (Inversed Fast Fourier Transformation) is processed, a guard interval is inserted at the beginning of each OFDM symbol, containing a copy of its last  
 10  $N_G$  samples ( $N_G$  = Samples of guard length).

The blocks of Fig. 1 and their respective function are briefly described in the following:

15 **Transmitter side** (upper part of Fig. 1):

Reference Number:	Description and Function:
1	Demultiplexer: The adopted frame structure consists of $n$ QPSK symbols followed by $m$ 16 QAM symbols. Thus $(n*2)$ bits are sent to the QPSK modulator 2, and $(m*4)$ bits are supplied to a 16 QAM modulator 3.
20	
2	QPSK Modulator: Mapping of 2 bits into QPSK complex symbols.
25	
3	16 QAM Modulator: Mapping of 4 bits into 16 QAM complex symbols.
30	
4	Multiplexer (MUX): Multiplexes QPSK and 16 QAM symbols into a frame, as shown in Fig. 6.
5	Phase-Differential Encoder: The phases of subsequent symbols on the same subcarrier are differentially modulated, whereas the amplitude is kept unchanged (see functional block diagram of Fig. 4).
35	

1	6	Null Symbol Generator: The unused subcarriers at the band edges are set to zero.
5	7	MUX: The data and null symbols are multiplexed into an OFDM symbol, where the subcarriers at the edges are equal to zero.
10	8	IFFT: Inverse FFT is performed on N data samples to produce a baseband OFDM modulated signal.
15	9	Insertion of guard interval: A copy of the last $N_G$ samples of the time domain OFDM symbol are inserted before each symbol in order to reduce the effect of multipath interference.
20	10	Quadrature Modulator: The input signal is used to modulate carriers having a $90^\circ$ phase difference.
	11	Digital-to Analogue converter (D/A-converter).
25	12	Up-Converter: The signal is converted by a frequency converter to a given carrier frequency for transmission.
	13	Radio Channel: The radio channels used for simulations are described further below in this chapter.

**Receiver side (lower part of Fig. 1):**

30	14	Down-Converter: The received signal is converted from the carrier frequency down to an intermediate frequency.
35	15	Analogue-to-Digital converter (A/D-converter).

1	16	Quadrature Demodulator: The OFDM signal is detected from the intermediate frequency and the baseband signal is generated.
5	17	Time Synchronization: A FFT window is generated indicating the effective symbol portion of the OFDM symbol for removing the guard interval.
10	18	FFT: Fast (discrete) Fourier Transformation is performed on the OFDM symbol to generate the complex frequency-domain symbols.
15	19	Demultiplexer (DEMUX): The input signal is demultiplexed into the useful data to be sent to a phase differential decoder 21 and the unused subcarriers at the band edges are removed in 20.
20	20	Delete unused subcarriers: The null symbols inserted by null symbol generator 6 at the transmitter are removed and deleted.
25	21	Phase Differential Decoder: The phases of subsequent symbols on the same subcarrier are differentially demodulated, whereas the amplitude is coherently processed (see block diagram implementation of Fig. 5).
30	22	DEMUX: According to the frame structure QPSK symbols are sent to a hardlimiter 23 and a running mean amplitude generation means 24 and the following QAM symbols are amplitude-corrected in 25.
35	23	Hardlimiter: The received QPSK symbols are hard-limited before demodulation.



1           **24**           Running mean of amplitude: Since the amplitude of  
the QPSK symbols is definitely "1", the amount of  
amplitude distortion each subcarrier is determined  
5           from the QPSK signal, and supplied to block 25 for  
correction of the amplitude of the QAM symbols.

**25**           Correction of amplitude: The amplitude of the  
received QAM symbols is corrected by the factor  
calculated by block 24.

10           **26**           QPSK Demodulator: Demapping of QPSK complex  
symbols into corresponding bits.

**27**           16 QAM Demodulator: Demapping of QAM complex  
15           symbols into corresponding bits.

**28**           MUX: Multiplexing of QPSK and QAM bits according  
to the adopted frame structure.

20 Two channel models have been considered for simulation: An additive white  
Gaussian noise channel (AWGN) and a frequency selective channel model  
proposed by ETSI (European Telecommunications Standards Institution) for  
the Universal Mobile Telecommunication System (UMTS). The latter is a Wide  
Sense Stationary Uncorrelated Scattering (WSSUS) channel model, that as-  
25 sumes that the received signal is represented by the sum of six delayed repli-  
cas of the input signal, weighted by independent zero-mean complex Gaussian  
time variant processes. The relative path loss and delay of each path for typical  
indoor environment is given in the Table 1 below:

30

Tap	Relative Delay (nsec)	Average Path Loss (dB)
1	0.0	0.0
2	50	-3.0
3	110	-10.0
4	170	-18.0
5	290	-26.0
6	310	-32.0

35

Table 1: Parameter of the multipath channel model  
used for simulations

- 1 On the receiver side the guard interval is first removed by windowing. The synchronization is not considered here. After the signal has been transformed into the frequency domain by FFT, the virtual carriers are extracted and the QAM demodulation is performed.

5

For the analysis the following system parameters have been used:

	FFT carrier size:	$N = 64$
	Guard length:	$N_G = 7$ samples
10	Useful time:	$N_{used} = 64$ samples
	Symbol time:	$N_{Sym} = 71$ samples
	Selected carriers:	$N_{sel} = 56$
	Sampling frequency:	$B = 30$ MHz

## 15 Chapter II: Coherent Modulation

- As mentioned above, in the case of coherent modulation pilot symbols should be inserted to help channel estimation in the receiver. Normally, each frame contains a number of pilot symbols on different subcarriers. In the receiver the amount of distortion of the pilot subcarriers is interpolated in the time and frequency domains, in order to estimate the channel response over the frequency band of interest.

- To simplify simulations it was assumed that one OFDM symbol with all subcarriers set to a known value ( $I = 1$ ,  $Q = 0$ ) is sent at the beginning of each frame. On the receiver side that OFDM symbol is first filtered using a complex FIR filter, in order to shorten the effect of additive white Gaussian noise. It is then used as a measure of channel distortion and the following data symbols are correlated by equivalent factors. The simulation results over AWGN and UMTS channels are shown in Fig. 2:

- Curve "a" shows an ideal demodulation condition for AWGN. Curve "b" visualizes the coherent demodulation of 16 QAM signals over an AWGN channel causing a SNR degradation of about 1dB at a BER of  $10E-3$ . This is due to the fact that the channel estimation factor for every subcarrier is gained from a noisy pilot symbol in spite of FIR filtering. Further SNR degradation of about 2,5 dB is observed, when a multipath channel UMTS is assumed (curve "c").

- 1 These results can be improved by averaging the channel estimation factors over several frames, thus the effect of additive white Gaussian noise can be further shortened.

### 5 **Chapter III: Quasi-Differential Modulation according to the Invention.**

- The reason why quadrature amplitude modulated (QAM) signals can not be differentially processed as with DQPSK is the multi-amplitude constellation of QAM signals. The result would be endless many amplitude levels after a few  
10 symbols have been differentially modulated. This is, however, an undesired property that complicates the implementation.

- Thus the idea of the invention is the separate handling of amplitude and phase of QAM signals. If only the phase of 16 QAM symbols are differentially modu-  
15 lated while keeping their original amplitudes, there would be endless many phase levels at three amplitudes (see Fig. 3). Of course, this is less bothersome than it is the case with many amplitude levels.

- As shown in Fig. 4 and Fig. 5 the phases of subsequent symbols  $\phi_k$  and  $\phi_{k-N}$ ,  
20 respectively on the same subcarrier are differentially modulated and demodulated, whereas the amplitude  $A_k$  is coherently processed.

- The phase rotation on every subcarrier is no more relevant. Preferably and in accordance with the invention the amplitude distortion of the QAM signal due  
25 to frequency selectivity of the channel is separately corrected. The information about the correcting factor for every subcarrier is preferably taken from the QAM symbols whose phase is unique to them. This is the case for all symbols not located at the diagonals of the Q/I diagram. In particular, this is the case for 8 of the 16 symbols as shown in the constellation diagram of Fig. 10D.  
30 Constellation diagrams for QPSK and 16 QAM symbols at different stages with an assumed SNR of 35 dB are depicted in Fig. 10A to 10F with the respective signal characterization indicated in the respective headline.

- The correcting factors for the amplitude can be easier computed when a  
35 combined QPSK/16 QAM system is adopted. Often, wireless broadband systems adopt QPSK modulation of control data, for better robustness in frequency selective channels, and 16 QAM or higher modulation for useful

1 data. In the system used for simulation, the frame structure of Fig. 6 has been  
 adopted comprising 200 OFDM symbols in the QPSK modulated control signal  
 and 4800 OFDM symbols in the 16 QAM modulated data signal, i.e., one frame  
 contains 5000 OFDM symbols.

5

Since QPSK symbols have definitely the amplitude "1", and the channel is  
 supposed to be static during one frame, the amount of amplitude distortion of  
 the QPSK signal can be easily determined and used for correction of the QAM  
 signal.

10

Furthermore, a running mean of the amplitude correcting factor can be per-  
 formed during the QPSK transmission, in order to shorten the effect of additive  
 white Gaussian noise.

15 If only 16 QAM signals are available, a running mean of the correcting factors  
 can also be performed over a time window, where the channel is supposed to  
 be static.

Quasi-differential demodulation in an AWGN channel causes a SNR degradation  
 20 of about 5.5 dB at a BER of  $10E-3$ ; see Fig. 7, curve "f" - compared to curve "d"  
 referring to an ideal AWGN channel. The BER performance over a multipath  
 channel UMTS is identical with that over an AWGN channel as visualized by  
 curve "e" in Fig. 7. This denotes, that the multipath effect is fully shortened  
 with the quasi-differential demodulation technique according to the invention.

25 The benefit of this new technique is therefore major in frequency-selective ra-  
 dio channels.

#### Chapter IV: Comparison of BER performance

30 The BER results of both techniques are depicted in Fig. 8 for AWGN and in Fig.  
 9 for the multipath channel.

Fig. 8 teaches that coherent modulation technique with channel estimation  
 performs considerably better than the quasi-differential modulation over the  
 35 AWGN channel. Curve "h" for the coherent modulation comes close to the ideal  
 curve "g" by approximately 1 dB, whereas curve "j" for the quasi-differential  
 technique shows a smaller decrease of BER as SNR increases.

1 However, the excellent performance of the 16 QAM quasi-differential modulation technique according to the invention becomes obvious when considering the multipath channel situation shown in Fig. 9. Curve "k" again shows for comparison the ideal situation for AWGN. The SNR degradation of curve "m" depicting the BER performance for quasi-differential demodulation according to the invention compared to the coherent demodulation of curve "e" is most at a BER of  $10E-3$ , and amounts to only 2 dB. For higher and lower BERs the degradation becomes constantly smaller.

## 10 Chapter V: Summary

A novel incoherent demodulation technique for QAM signals has been presented. The BER performance of this technique has been analyzed and compared to the coherent one.

15 It can be concluded that the advantage of the coherent demodulation is the SNR gain of maximum 2 dB at a BER of  $10E-3$ . However, this can be further minimized when the additional overhead for channel estimation is used for higher coding of the quasi-differential modulated signal.

20 Furthermore, when considering the implementation aspects of both techniques compared here, it should be noticed that the differential technique according to the invention is less complex since the frequency synchronization of differential demodulated signals is easier. In particular, complex equalizers to perform channel estimation are no more needed as for coherent systems. Also, no pilot subcarriers are needed and thus the bandwidth efficiency is much higher.

30

35